Design and Implementation of an Intelligent Irrigation System Based on Multi-Sensor Fusion

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Abstract: Aiming at the problems of one-sided sensor perception, rigid decision-making models, and insufficient scene adaptability in the current intelligent irrigation field, this paper designs and implements an irrigation solution integrating multi-dimensional perception and intelligent decision-making based on the actual needs of farmland production. The system constructs a three-dimensional perception network of "soil moisture-crop physiology-meteorological environment", integrates data from various high-precision sensors, processes multi-source heterogeneous data through a hierarchical data fusion algorithm, and builds an adaptive irrigation decision-making model combined with machine learning algorithms, realizing the upgrade from "passive water supplementation" to "active adaptation". The hardware adopts standardized interfaces and redundant design, and the software incorporates energy consumption optimization logic. Field tests show that compared with traditional irrigation modes, the system increases water resource utilization rate by 28.3% and average crop yield by 13.6%, providing a feasible practical scheme for modern agricultural irrigation.

Keywords: Multi-sensor Fusion; Intelligent Irrigation; Machine Learning; Adaptive Decision-Making; Precision Agriculture

1. Introduction

1.1 Research Background and Significance

Water shortage is a core bottleneck restricting the sustainable development of global agriculture. Agricultural irrigation water consumption accounts for more than 60% of the total water consumption in China, but the water resource utilization rate of traditional irrigation methods is only 30%~40%, resulting in serious waste. Against the background of frequent extreme weather, extensive irrigation exacerbates the contradiction between supply and demand of water resources, making it difficult to match the water demand of crops in different growth stages and affecting the yield and quality of agricultural products.

Current intelligent irrigation systems have many problems: over-reliance on a single soil moisture sensor leads to one-sided monitoring, fixed irrigation parameters have poor adaptability, sensors are susceptible to interference, and data accuracy and system stability are insufficient. The intelligent irrigation system based on multi-sensor fusion integrates multi-dimensional data and realizes precise decision-making combined with intelligent algorithms, which can maximize the efficiency of water resource utilization, reduce waste, match water supply with crop growth rhythm, reduce labor costs, promote the transformation of agriculture from "experience-driven" to "data-driven", and provide support for food security and green and sustainable agricultural development.[1]

1.2 Research Status at Home and Abroad

Foreign intelligent irrigation technology started early and has mature applications. Israel combines multi-sensor fusion technology with drip irrigation systems, with water resource utilization rate exceeding 90%; the United States builds large-scale farm irrigation platforms relying on the Internet of Things technology to achieve cross-regional precision irrigation. These systems have in-depth data fusion and mature decision-making models, adapting to large-scale agricultural production.

In recent years, certain progress has been made in the field of intelligent irrigation in China, but there is a gap compared with the international advanced level: the accuracy and stability of core sensors are insufficient, multi-source data fusion algorithms are superficial, decision-making models lack flexibility, the long-term operation reliability of the system in complex environments needs to be verified, and technology promotion is limited to large-scale farms. Therefore, it is of great significance to develop an intelligent irrigation system with precise perception, intelligent decision-making, stable operation and high adaptability.[2]

1.3 Research Content and Technical Route

1.3.1 Research content

Centering on the three core goals of "precise perception-intelligent decision-making-stable operation", the key research contents are as follows:

(1) Construct a three-dimensional perception system, select high-precision sensors, optimize the layout scheme, and improve data accuracy and consistency through data preprocessing and hierarchical fusion algorithms.

(2) Mine data correlations based on machine learning algorithms, introduce transfer learning and crop physiology knowledge, and build an adaptive irrigation decision-making model.

(3) Complete the integrated development of system software and hardware, and adopt standardized interfaces, redundant backup and energy consumption optimization strategies to ensure the stable operation of the system in complex farmland environments.

1.3.2 Technical route

Following the idea of "problem-oriented-scheme design-system implementation-experimental verification": clarify the needs and pain points through literature research and field investigation; tackle key technologies such as sensor selection, data fusion algorithm and decision-making model construction; complete the integration of software and hardware; verify the performance and optimize parameters through field tests to form a mature solution.

2. Related Technical Foundations

2.1 Multi-Sensor Fusion Technology

Multi-sensor fusion technology integrates data from different sensors through algorithms, and uses data redundancy and complementarity to make up for the limitations of a single sensor. Fusion technologies are divided into three categories: data-level, feature-level and decision-level. This study adopts a hierarchical fusion strategy: weighted average method is used for data-level fusion to improve data consistency; Kalman filter is used for feature-level fusion to reduce environmental interference; CNN network is used for deep feature fusion to mine complex correlations between data.

2.2 Machine Learning Algorithms

Machine learning algorithms are the core support for intelligent irrigation decision-making. Random forest algorithm is suitable for analyzing the nonlinear relationship of agricultural data, and LSTM neural network is good at capturing the long-term dependence characteristics of time series data[2]. Transfer learning technology is introduced to reduce the dependence on sample data and improve the scene adaptability of the model. This study combines the two algorithms to build a crop water demand prediction model, realizes the adaptation across crops and growth stages through transfer learning, and corrects the model output combined with crop physiology knowledge.

2.3 Hardware and Communication Technology

Sensors need to meet the requirements of complex farmland environments and have low power consumption characteristics; the controller selects STM32F407 microcontroller with rich interfaces and strong data processing capabilities; the execution mechanism includes solenoid valves, variable frequency water pumps, etc.; the communication module adopts LoRa wireless communication technology, which has low power consumption, long distance and strong anti-interference ability, adapting to the communication needs of large-scale farmland.[3]

3. Overall System Design

3.1 System Architecture Design

The system adopts a four-layer architecture of "perception layer-network layer-decision layer-execution layer". The perception layer is composed of various sensors to collect multi-dimensional data; the network layer takes LoRa technology as the core to build a data transmission channel; the decision layer generates irrigation control instructions through data fusion and analysis; the execution layer is responsible for accurately executing irrigation operations.[4]

3.2 Core Function Design

3.2.1 Multi-dimensional data collection function

Synchronously collect three types of data: soil, crop and meteorology. Soil data includes humidity and temperature at different depths; crop data includes physiological indicators such as leaf water potential; meteorological data includes environmental factors such as air temperature and humidity. The collection frequency is dynamically adjusted according to the crop growth stage.

3.2.2 Data fusion and preprocessing function

After the data is processed by wavelet transform denoising, linear interpolation completion and Z-score standardization, hierarchical fusion is completed through weighted average method, Kalman filter and CNN network to improve data reliability and effectiveness.

3.2.3 Adaptive irrigation decision-making function

Construct an association database of "environment-crop status-water demand", predict crop water demand based on random forest and LSTM algorithms; introduce transfer learning technology to quickly adapt to different crops and growth stages; correct irrigation parameters combined with crop physiology knowledge.

3.2.4 Remote monitoring and control function

Equipped with a host computer platform and a mobile terminal APP, it realizes real-time data viewing, historical query, parameter setting, remote control and alarm functions, supporting flexible switching between automatic control and manual intervention.[5]

4. System Hardware Design

4.1 Sensor Selection and Layout

4.1.1 Sensor selection

The soil moisture sensor is a TDR type with an error of ≤±2%; the leaf water potential sensor is a portable high-precision model with an error of ≤±0.05MPa; the meteorological sensor is an integrated type that meets the needs of all-weather monitoring; all sensors are designed with low power consumption and can last for more than 6 months.

4.1.2 Sensor layout scheme

Adopt the "grid + key area" strategy: the test field is divided into 10m×10m grids, and 3 soil moisture sensors at different depths are vertically arranged in each unit; leaf water potential monitoring points are set every 50m in the middle of the crop planting row; meteorological sensors are arranged in open areas; the rainfall sensor is installed at a height of 1.5m from the ground.

4.2 Control Module Design

Taking STM32F407 microcontroller as the core, it integrates data collection, communication, power management and execution control units. The sampling rate of the data collection unit reaches 1kHz; the communication unit adopts SX1278 LoRa module; the power management unit supports solar charging expansion; the execution control unit realizes stepless adjustment of irrigation flow.

4.3 Selection of Execution Mechanism

The solenoid valve selects DN25 caliber model with IP65 protection level; the variable frequency water pump is of centrifugal structure and supports variable frequency speed regulation; all execution mechanisms adopt standardized interface design and support hot swapping.

5. System Software Design

5.1 Overall Software Architecture

Adopt modular design, which is divided into six modules: data collection, preprocessing, fusion, decision-making model, execution control and upper computer interaction, and realize efficient communication through data bus.

5.2 Core Algorithm Implementation

The core algorithm implementation is centered on the whole process of data processing and irrigation decision-making, first carrying out data preprocessing on the collected multi-source heterogeneous data, including wavelet transform denoising, time series interpolation and Z-score standardization, through which the noise interference in the original data is eliminated, the missing data is supplemented and the data is normalized to ensure that the data quality meets the subsequent algorithm processing requirements; then adopting a hierarchical fusion strategy for the preprocessed valid data, completing data-level fusion with the weighted average method to improve data consistency,[6] implementing feature-level fusion with the Kalman filter to reduce environmental interference, and conducting deep feature fusion with the CNN network to fully mine the complex correlations between various monitoring data; finally, building a crop water demand prediction model based on field test data, optimizing the model by introducing transfer learning technology and crop physiology knowledge, combining the advantages of random forest and LSTM algorithms to realize accurate prediction of crop water demand and flexible adaptation of the model to different crops and their different growth stages, and taking MSE and R^2 as the evaluation indicators of the model to test and optimize its performance, so as to output scientific and reasonable irrigation parameters and support the realization of adaptive irrigation decision-making function.

6. System Tests and Result Analysis

6.1 Test Design

The test site is an agricultural demonstration park, with a total area of $2000m^2$ of test fields, including $600m^2$ for wheat, $600m^2$ for corn, $600m^2$ for vegetables, and $200m^2$ reserved as a control area. The test cycle is 1 year. The test group adopts this system, and the control group adopts the traditional flood irrigation method. The sensor perception accuracy, system stability, water resource utilization rate and crop yield are monitored.[7]

6.2 Test Results and Analysis

6.2.1 Perception accuracy analysis

After multi-sensor fusion processing, the measurement error of each key indicator is controlled within 3%, which is 15%-25% higher than that of a single sensor.

The table below compares the measurement errors and accuracy improvement rates of key monitoring indicators such as soil moisture and leaf water potential between single-sensor detection and post-fusion processing, visually demonstrating the remarkable optimization effect of multi-sensor fusion technology on perception accuracy.

Table 1. Comparison of Sensor Perception Accuracy

Measurement Index	Error of Single Sensor	Error After Fusion	Accuracy Improvement Rate
Soil Moisture	±3.2%	±1.8%	43.75%
Leaf Water Potential	±0.08MPa	±0.04MPa	50.00%
Air Temperature	±0.8℃	±0.4℃	50.00%
Light Intensity	±5.2%	±2.9%	44.23%

6.2.2 Water saving and yield increasing effect analysis

The irrigation water volume of the test group is 26.2%-31.2% less than that of the control group, and the average water resource utilization rate is increased by 28.3%; the average crop yield is increased by 13.6%, realizing water saving, efficiency improvement and quality improvement.

Taking wheat, corn and vegetables as the research objects, this table contrasts the irrigation water volume, water saving rate, crop yield and yield increase rate under the traditional flood irrigation mode and the irrigation mode of this system, clearly presenting the dual benefits of water conservation and yield increase of the system.

Table 2. Comparison of Irrigation Water Volume and Crop Yield

Crop Type	Irrigation Water Volume of Control Group ($m^3/667m^2$)	Irrigation Water Volume of Test Group ($m^3/667m^2$)	Water Saving Rate	Yield of Control Group ($kg/667m^2$)	Yield of Test Group ($kg/667m^2$)	Yield Increase Rate
Wheat	320	220	31.2%	520	595	14.5%
Corn	280	203	27.5%	650	733	14.5%
Vegetables	450	332	26.2%	4800	5448	13.5%

6.2.3 System stability analysis

The system has been running for more than 8000 hours, with an average mean time between failures of 4000 hours. It still runs stably under extreme weather, and the data transmission success rate reaches 99.2%.

7. Conclusions and Prospects

7.1 Research Conclusions

(1) A three-dimensional perception system is constructed, and the perception accuracy is improved through hierarchical data fusion algorithms, with the error of key indicators controlled within 3%.

(2) An adaptive irrigation decision-making model is proposed to realize flexible adaptation to different crops and growth stages.

(3) The integrated development of system software and hardware is completed to ensure the long-term stable operation of the system in complex farmland environments.

(4) Field tests verify that the system increases water resource utilization rate by 28.3% and average crop yield by 13.6%, and has good application value and promotion prospects.

7.2 Research Limitations and Prospects

There are limitations in the research: the decision-making model does not fully consider factors such as soil texture, the hardware cost is relatively high, and the LoRa communication transmission distance is limited in complex terrain. In the future, we will optimize the decision-making model, develop low-cost schemes, build a hybrid communication network, and develop intelligent operation and maintenance functions for mobile terminals to improve the practicality and promotion of the system.[8]

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